Analysis of active figure control effects on mounting strategy for x-ray optics

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Outline

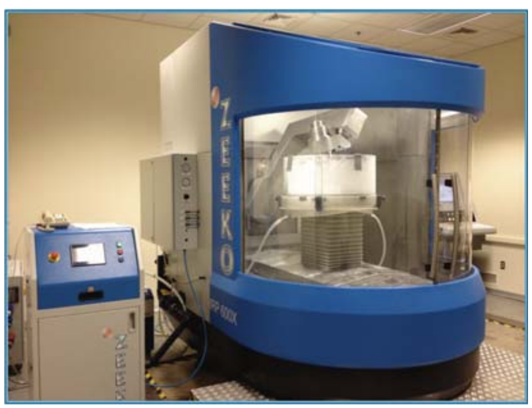
- Overview and Motivation
- Key Questions
- Approach
- Modeling Methods
- Model Validation
- One-D illustration.
- 2-D Flat illustration.
- 2-D shell segment.
- Shell Optical Performance vs. Mounting parameters
- Conclusions

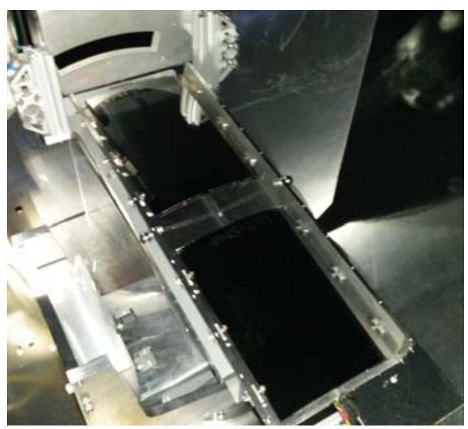
Overview and Motivation

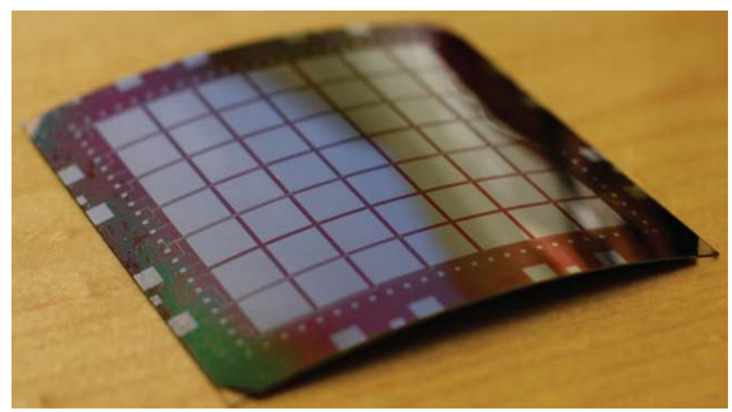
- Manufacturing process development and product design with the goal of performance optimization within specified constraints can often involve a very large trade space.
- Not only the selection of technological methods and design parameters, but the sequence of process steps can significantly influence the resulting performance.
- Such efforts benefit from the early development of high-fidelity simulations, which can illuminate the tall poles and guide the choices toward performance optimization.
- Ideally these simulations would provide an integrated end-to-end picture of the entire process so that one option can be weighed against another, i.e. to investigate strategic alternatives.
- We anticipate that the manufacturing process required for the production of large-area actively-controlled x-ray optics modules falls into this category.

Overview and Motivation

- At MSFC, we are involved in several technology development efforts for higher resolution / larger area / lighter weight x-ray optics.
- All of these technologies share the need to be mounted/assembled/aligned into modular units for testing or for flight.
- We have identified a requirement to develop the capability to assess the impact of mounting options on performance.
- The goal is to develop an optimal mounting strategy or a small set of testable strategic options for any specified x-ray optics technology, which would be applicable to the fully-developed manufacturing process.
- We are in the very early stages of developing this capability for active optics, so results, so far, are relatively simplistic and naive.
- Nevertheless, we feel that including active optics mounting strategies in our repertoire will help to drive our understanding of technical challenges and capabilities to overcome them to a higher level in the future.

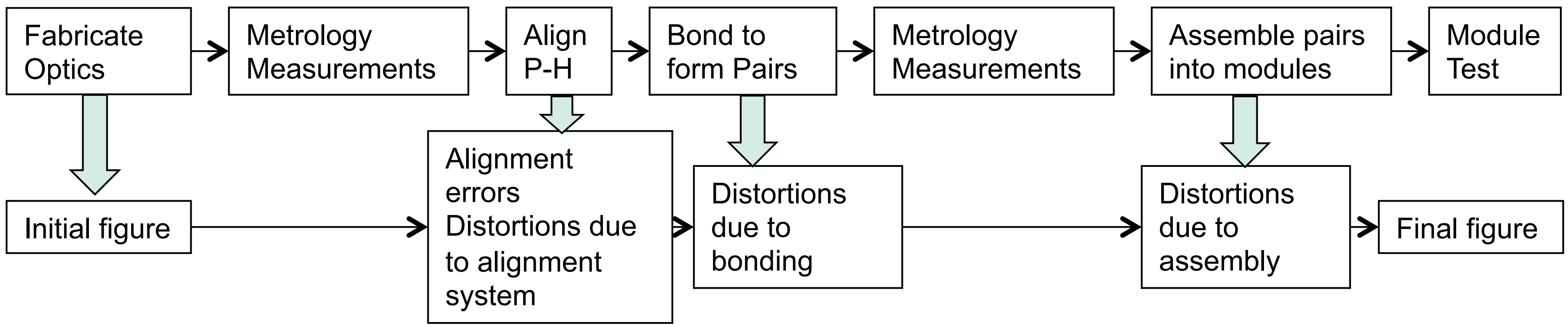






Posing Key Questions

- The process involved may be very complex



- Key questions for mounting strategy
  - What kind of distortions are uncorrectable by bimorphs?
  - How are uncorrectable distortions minimized?
    - Which design parameters?
    - Which process techniques?
    - In what sequence are processes performed?

Approach

- Since this is virtual development, we use simulations to begin to answer key questions
- Steps:
  - generate large samples of initial figure error maps
  - develop deflection models based on plate/shallow shell theory and validate against FEM
    - Develop and apply boundary conditions as appropriate to address the question in terms of figure distortions
  - compute influence function basis for response to piezo actuation "voltage"
  - fit basis to initial figure + distortions to determine final figure which minimizes RMS axial slope errors or RMS 2-reflection ray divergence
  - Compare results from configuration alternatives

Modeling Methods

- Monte carlo technique to generate figure error maps
  - Probably should just operate on Fourier components instead.
- Finite difference deflection model based on Kirchhoff's plate bending theory (1850), and Donnell-Mushtari-Vlasov shallow shell theory.(Ventsel & Krauthammer, 2001)
  - Numerically solve "biharmonic" equation with boundary conditions
    - approximate piezo with a force distribution
  - For curved plates plan to solve a pair of 4th order equations with boundary conditions (not yet implemented)
    - For now using influence functions from FEM (Carolyn Atkins) for curved plates
- Rationale
  - Quicker to run, implemented in Mathematica®
  - No additional expense and training
  - No need to take time from trained FEM experts

Kirchhoff:

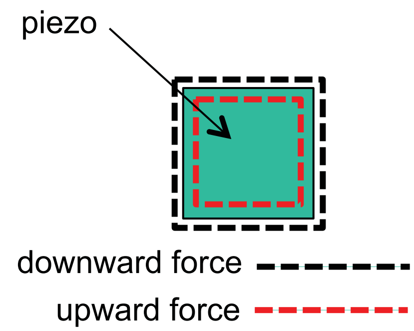
$\nabla^4\eta(x,y) = p(x,y)/D$,
$\eta(x,y)$ = deflection in plate coordinates,
$p(x,y)$ = pressure distribution orthogonal to the plate, and
D = flexural rigidity $= \frac{Eh^3}{12(1-\nu^2)}$,
where E = is Elastic Modulus,
h = thickness, and
ν = Poisson's Ratio.

DMV:

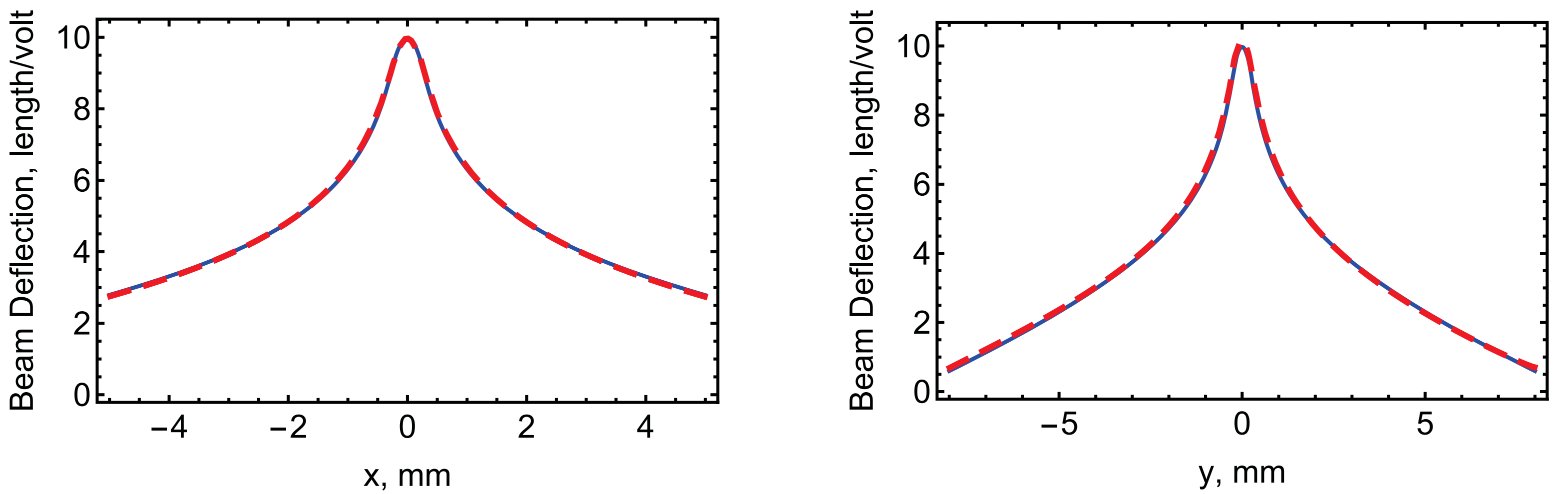
$\nabla^4\eta(x,y) = (p(x,y) + \frac{1}{R\cos^2\frac{\Theta}{4}}\frac{\partial^2\Phi(x,y)}{\partial y^2})/D$,
$\nabla^4\Phi(x,y) = -Eh\frac{1}{R\cos^2\frac{\Theta}{4}}\frac{\partial^2\eta(x,y)}{\partial y^2}$,
$\Phi(x,y)$ = Airy stress function,
Θ = shell azimuthal extent, and
R = shell radius.

Model Validation

- Compared finite difference(FD) solutions to FEM solutions with modeled piezos
  - 16 cm x 10 cm simply constrained flat
  - 5 mm x 5 mm piezo with 0.5 mm separation
  - 0.4 mm thick glass
  - 0.2 mm thick piezo
- FEM mesh is automatically generated (Comsol®)
- FD is on 0.25 mm grid (x elements)
- FD approximates piezos with a distribution of localized forces
- Agreement is very good.



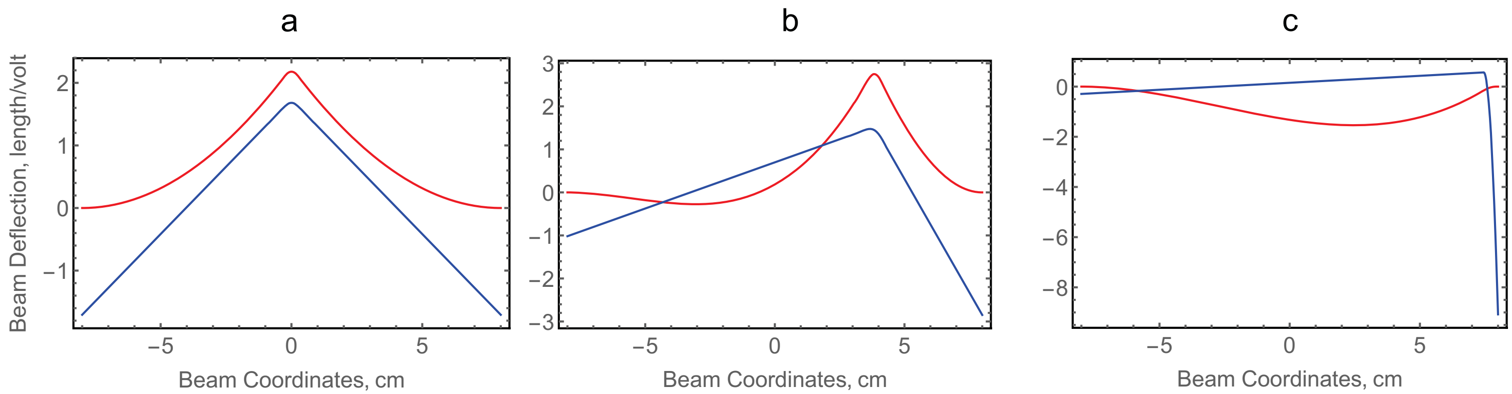
2-D influence functions for FD (solid blue) and FEM (dashed red)



One-D illustration

- Use simple beam theory to illuminate questions in 1 dimension

- Fixed mount vs. simply supported
  - Influence functions are obviously different for a beam with fixed ends, vs. an unconstrained beam



- Actuator effectiveness depends on position
- Actuators are relatively ineffective near mounting points
- Completeness of resulting basis composed of the full set of influence functions is affected by mounting → Performance improvement is affected

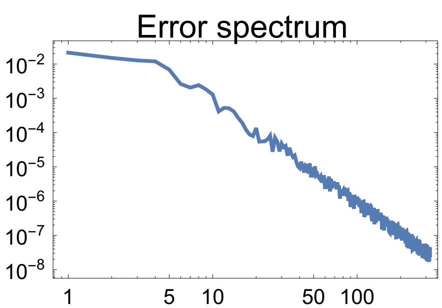
One-D illustration II

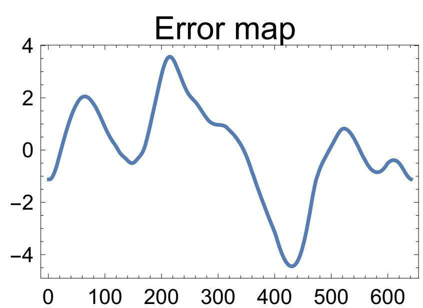
- Begin to quantify effects using simulated error maps
- Assume a surface error spectrum

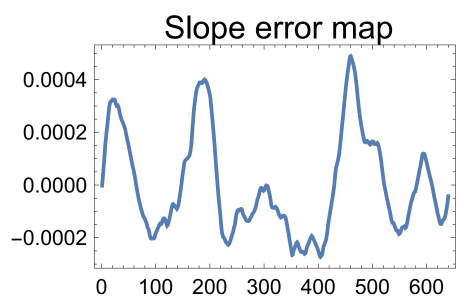
$$f(\sigma_s, \omega) = \sigma_s \sqrt{\frac{\sin\frac{3\pi}{k}}{\pi(k-3)\lambda} \frac{k\lambda^{k-1}}{\lambda^k + \omega^k}},$$

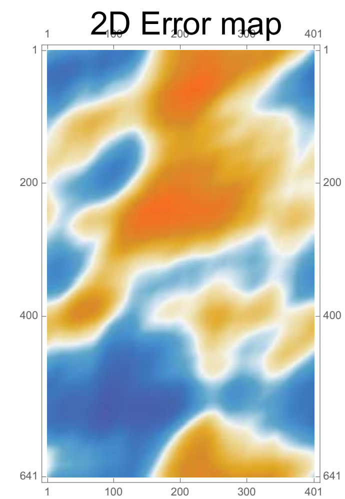
where σ_s is the RMS slope error,
ω is the spatial frequency,
k is the assymptotic power law index and,
λ is a cutoff parameter to tune the low frequencies.

- Surface map is the discrete inverse Fourier transform of the above spectrum
- Monte Carlo phases $\pm\pi$ and 0.5–2x amplitudes to generate a series of similar surface maps
- Adjust λ to match adjustability response which cuts off at Nyquist of piezo frequency.
- Adjust k to control high frequency content, performance floor
- For 2D let: $\omega^2 \rightarrow \omega_{\mathrm{ax}}^2 + \omega_{\mathrm{az}}^2$ for axial and azimuth frequencies



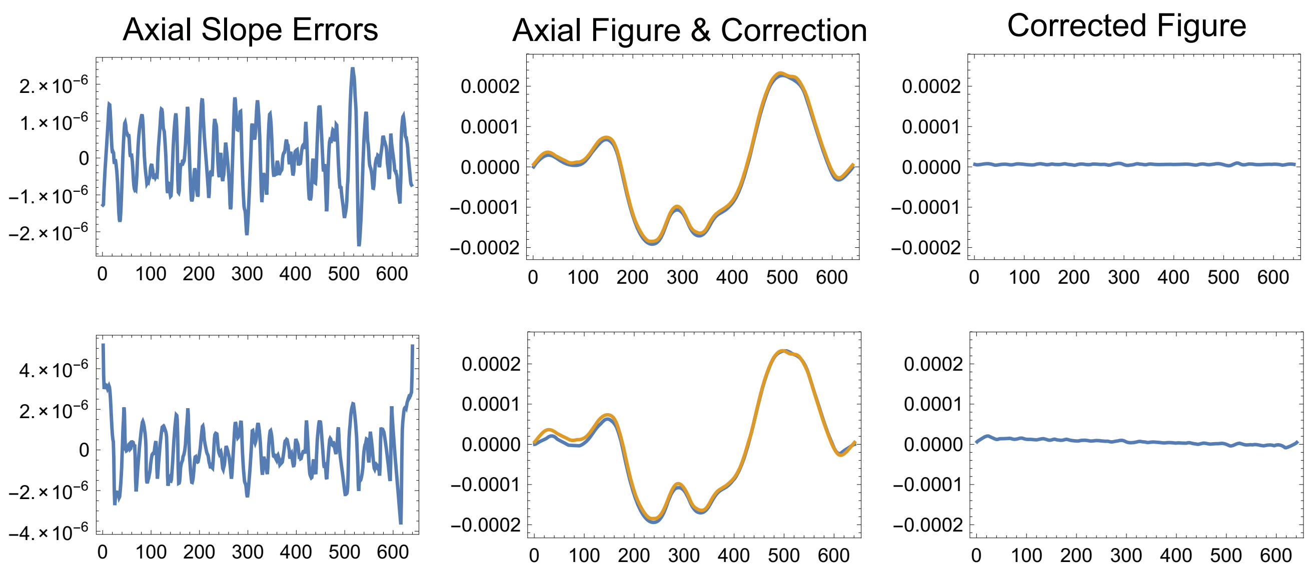






One-D illustration III

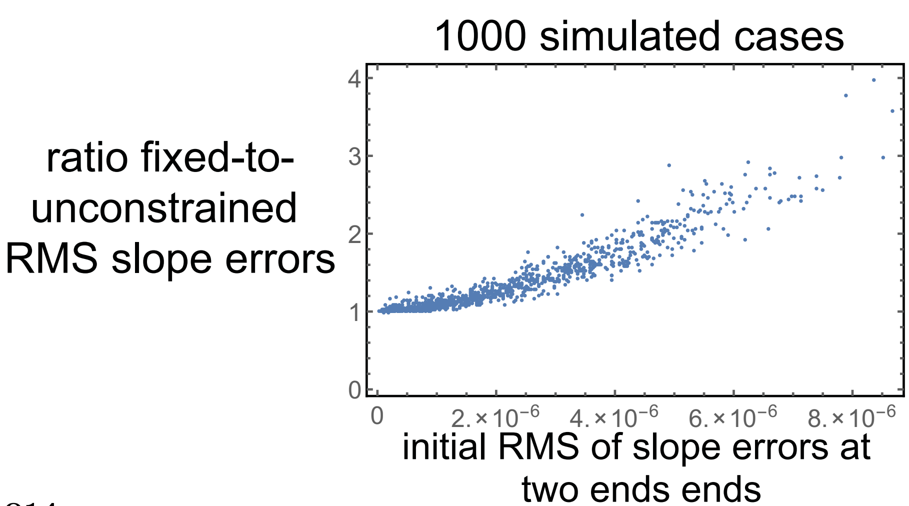
- Unconstrained (upper) vs. fixed (lower)



Initial RMS slope errors:
4.4 arcsec

After unconstrained adjustment:
0.48 arcsec

After adjustment in fixed configuration:
0.71 arcsec

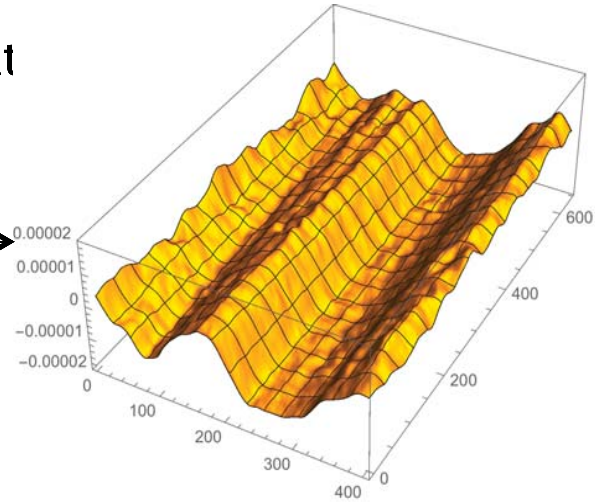


Mounting with adjusters activated would generally yield improved performance

2-D Flat illustration

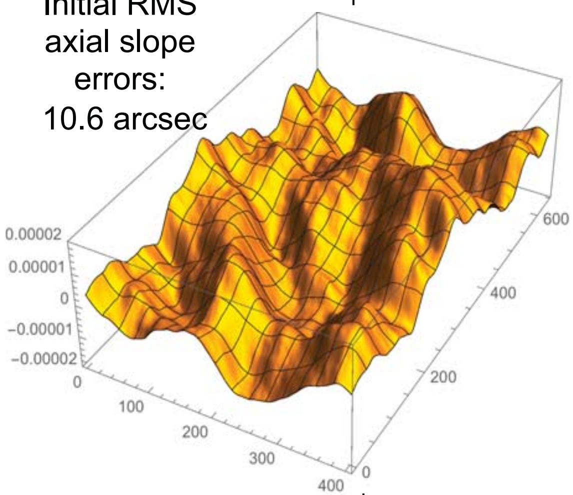
- Similar analysis for a 2-D flat plate

Optimize for RMS axial slope error

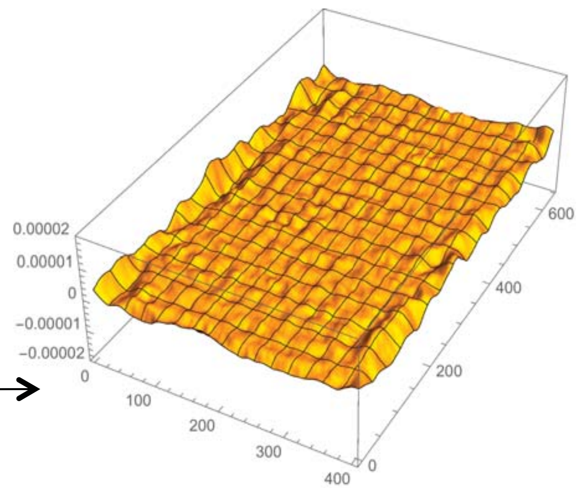


RMS axial slope errors: 3.0 arcsec

Initial RMS axial slope errors: 10.6 arcsec



Optimize for RMS deviation from prescription

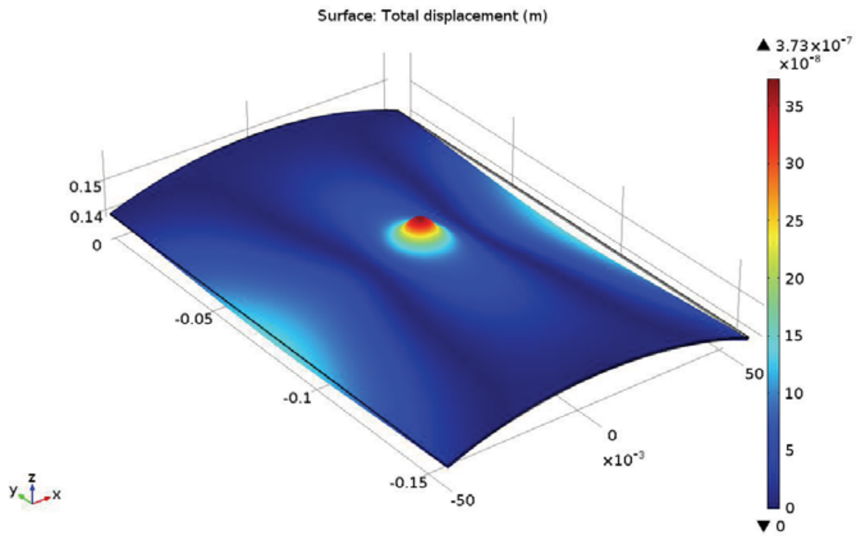


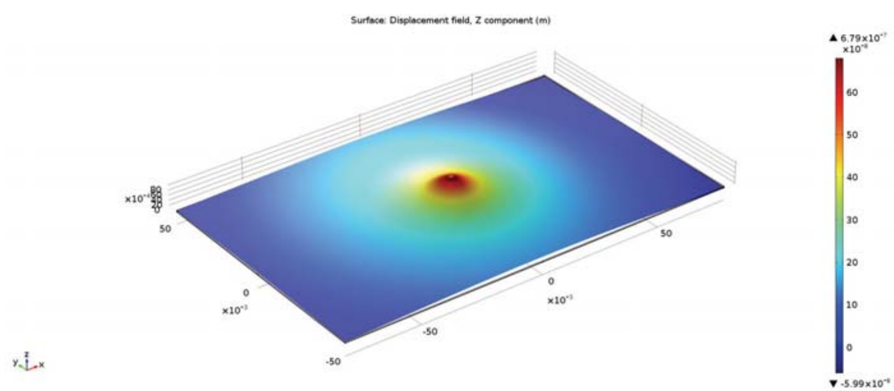
RMS axial slope errors: 3.5 arcsec

- Which results in better performance after mounting?

2-D shell segment

- Differences in influence functions





- Influence functions on curved optics can differ significantly from flat.
  - due to the effective rigidity caused by the curvature
  - The central displacement/volt is smaller.
  - The edge displacement/volt is about the same.
  - The surface deforms more along the azimuthal direction than the axial direction
- So edge displacement for a given central displacement is larger.
  - This must be included in the analysis of mounting distortions

Shell Optical Performance vs. Mounting parameters II

- Some sample end-to-end trade spaces

Adjusted performance of initially 10 arcsec optics (arcsec)

	k: asymptotic power law index:	3	3.5	4
Dimensions	Case			
1	unconstrained beam	0.9	0.7	0.4
1	fixed ends beam	1.4	1.1	0.9
2	unconstrained mirror surface	0.9	0.7	0.4
2	3 fixed points mirror surface	1.2	0.9	0.7
2	4 fixed points mirror surface	1.4	1.1	0.9
2	6 fixed points mirror surface	1.8	1.3	1
2	aligned unmatched pairs	1.3	1.0	0.6
2	aligned adjust 1 mirror only	1.4	1.0	0.6
2	aligned matched pairs	1.2	0.9	0.5
2(R = 15 cm)	unconstrained mirror surface	0.9	0.7	0.4
2(R = 15 cm)	3 fixed points mirror surface	1.2	0.9	0.7
2(R = 15 cm)	4 fixed points mirror surface	1.4	1.1	0.9
2(R = 15 cm)	6 fixed points mirror surface	1.8	1.3	1

Conclusions

- Expect that considering mounting strategy early, and allowing some flexibility in options could lead to better overall result
  - NOT: given mounting, what's the best optical configuration
  - NOT: given optics, what's the best mounting
  - INSTEAD: given nothing, what's the best combination of design parameters, technologies and processing sequence.
- Considering adjustable x-ray optics in a non-specific context, while something of an exercise, helps us to quickly come in-tune with significant mounting issues, in addition to producing some interesting strategic principles.
- We plan to:
  - Expand the finite difference approach to curved segments (shallow shells) and full shells
  - Develop an interface to efficiently investigate larger parameter spaces
  - Develop and test prototypes of promising concepts
- Attention to mounting details will obviously not improve optical system performance by orders magnitude but may lead to factors in the 1.4-2 range.